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Engineering Students for the 21st Century: Student Development Through the Curriculum

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ABSTRACT

Through support of the National Science Foundation's Department Level Reform program, *Engineering Students for the 21st Century* (ES21C) has implemented a ten-course sequence designed to help students develop into engineers. Spread across the Electrical and Computer Engineering (ECE) curriculum at Oklahoma State University, these courses were supported by engaging graduate students, building infrastructure to scaffold student development, and self-reflection on what it means to develop as an engineer. Four case studies from the spectrum of courses illustrate the on-going changes. While the project is still in the process of measuring changes in student learning and attitudes, preliminary project evaluation results are presented along with how formative evaluation has changed the project direction. From participants' experiences, both expected and unexpected, some of the factors that contribute to project successes and failures are outlined. A key finding is that the journey of reforming undergraduate programs needs to be guided by knowledge of both current location and destination. A taxonomy developed under this project to guide, discuss, and measure reform efforts is introduced that helps faculty map pathways to meaningful reform.

Keywords: department level reform, student development, engineering taxonomy

INTRODUCTION

"…there is nothing more difficult to take in hand, more perilous to conduct, or more uncertain in its success, than to take the lead in the introduction of a new order of things.

> *Because the innovator has for enemies all those who have done well under the old conditions, and lukewarm defenders in those who may do well under the new*."
>
> —Nicolo Machiavelli, *The Prince*, chapter VI

Decades of research on how engineering students learn has resulted in breakthroughs; there is consensus by experts on effective pedagogy. Although this consensus presents engineering educators with unprecedented opportunities to improve student learning, effective pedagogy has entered the classroom at a glacial pace. Widely read reports of expert panels (National Research Council 2004, 2005, 2007, 2009 Hyperlink to these resources) have found that despite the progress in research on how engineering students learn, engineering enrollments are lagging, women are not significantly better represented, and under-represented groups have made little progress. In addition, the ballooning cost of higher education, which puts college out of reach for an increasing number of students, is primarily supporting administration and research rather than education (Wellman et al. 2009). There is increasing concern that a proportionally decreasing number of technologically innovative graduates will result in a future decline in economic competitiveness.

NSF's Department Level Reform (DLR) program explored means of fostering effective and sustainable change in university programs to better and more efficiently educate engineers. Unlike many current efforts in engineering education, the DLR program recognized that difficulties in reforming engineering education may be structural as well as pedagogical. Department-level reform created experimental test-beds of alternative educational structures and methods that addressed pervasive problems involving a broad array of stakeholders. To succeed in this undertaking, reform projects attempted to change entrenched departmental cultures. As the Machiavelli quote at the start of this section implies, cultural change is a difficult undertaking with a long time constant; at meetings of DLR grantees many participants felt as if they were trying to fit ten years of work into a three year project.

This paper provides a brief and transitory glimpse of changes in one degree program undertaking reform. Curriculum reform is multi–faceted, uncertain, and involves negotiation between participants, each of whom have their own beliefs and goals. Reform is also an on–going process, if this paper had been written a year ago some perspectives might be different, as they will be different a year hence. To try to capture this complex, dynamic process, this paper differs from more traditional engineering education papers in three ways. First, the multifaceted nature of reform made it difficult to choose a single theoretical lens with which to view the project. The project integrated multiple pedagogies and allowed faculty in individual courses to choose their own approach to reform. Thus the view is more like that of a bug's eye than a camera lens; many small overlapping images need to be processed to make a complete picture. To create as coherent a picture as possible from the efforts of many participants—some of whom did not agree with all aspects of the reform effort—this paper was written by two participants, with input and dissenting opinions solicited from others involved in the project. Second, reform, as Machiavelli understood, is a difficult endeavor with a long time constant. Successfully reforming a program requires participants maintain momentum against damping forces. The energy to keep going was supplied by the passion of participants supported by the positive feedback of seeing how change impacted students. This paper tries to convey some of this emotional energy. Third, this paper seeks to capture changes across a program rather than in a single course. To keep the paper to a manageable length, many courses are not discussed in detail. Also, the paper does not fully explore all the paths that led to dead ends. Rather to effect and support change in other programs, this paper focuses primarily on what has proven effective and constant over time.

ENGINEERING STUDENTS FOR THE 21ST CENTURY

This section, divided into four subsections, describes the reform project. The first section outlines the vision at the start of the project and the basis for undertaking reform. The second section provides some information about the program that was reformed and the initial, planning phase of the reform project. Many of the initial ideas attempted in the planning phase did not work as planned. The third section reports on the strategy used to implement the project. The final section outlines the foundation in learning science by describing the theories and pedagogies the project is based upon.

Beliefs, Vision, and Assumptions

Engineering students learn what we teach them, but often do not become what we intend them to. The behaviors that let students succeed in classes do not always correlate with the behavior required to succeed in engineering careers. *Engineering Students for the 21st Century* (ES21C) is trying to align the behaviors that are taught in our program with those that help students succeed in engineering careers. To accomplish this goal ES21C is attempting to transition a subset of classes in the degree program from focusing on knowledge acquisition to emphasizing student development as engineers.

At the heart of *Engineering Students for the 21st Century* is the recognition that degree program offered at the start of the project was primarily knowledge-based. In this knowledge-based program the engineering degree was defined by a specific set of content students must learn; i.e. "*If you* *learn these things you will get a degree that certifies you are an engineer*." This characterization was certainly not monolithic throughout the department, while approximately 15% of the faculty were engaged in developing a broad spectrum of student skills, efforts were not coordinated or focused. An inherent assumption of this knowledge-based paradigm is that by learning specific content students will be able to function as engineers. Knowledge-based programs thrived in a world where the specialized information needed for engineering could only be found and learned at universities. In an age where the internet makes engineering knowledge widely available, the long term sustainability of this model is questionable. As Eli Noam (Noam 1995) noted more than a decade ago: "*Today's production and distribution of information are undermining the university structure, making it ready to collapse in slow motion once alternatives to its function become possible.*"

Engineering Students for the 21st Century seeks to make programs development-based rather than knowledge-based by creating a set of classes focused on developing the broad set of skills students need to understand problems in depth. To develop both knowledge and skills, students are walked through the process of solving the problem while learning concepts needed to understand the problem. The project posits that it is of greater importance to develop the skills needed to solve in-depth problems than to try to cover a large breadth of content in electrical engineering. In ES21C in-depth research or design projects become key experiences in a diverse curriculum.

To engender the cultural change needed to support the shift from knowledge acquisition to skill development, it is critical to address not only what and how students learn but also how faculty support learning and the learning environment. In ES21C the role of faculty changes from lecturers to mentors and scholars, guiding academic development towards complex problem solving tied to real world problems. Development-based classes attempt to create overlap between what engineers need to learn (Practice of Engineering), what students are motivated by (Perception of Engineering), and creating an environment that facilitates learning (Teaching Engineering) as shown in the Venn diagram of Figure 1.

Under ES21C a small subset of the courses (approximately 25%) in the electrical engineering program were, and continue to be, modified to focus on student development. The goal of ES21C is to have one course each semester of the program that emphasizes student development, with all the development courses sharing a common strategic approach. These courses make course material relevant by teaching course content in the context of a project while building teamwork and communication skills. Within this strategic framework, each faculty member is free to choose topics and teaching techniques appropriate to their course and their own beliefs about learning and teaching.

In summary, the vision of *Engineering Students for the 21st Century* is to shift the focus of an engineering degree from knowledge to developing the broad array of skills and knowledge needed

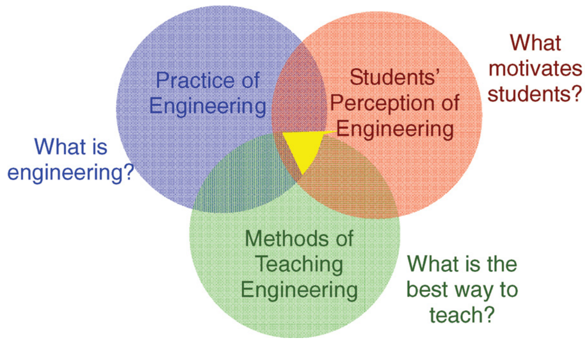

Figure 1. Courses which focus on student development are hypothesized to be effective when effective pedagogy, actual engineering practices, and relevance to students overlap.

by practicing engineers. The experiences gained will hopefully contribute to the sweeping realignment of engineering programs in U.S. universities called for by the National Academy of Engineering, National Science Foundation, and National Research Council (National Research Council 2004, 2005, 2007, 2009 Hyperlink to these resources).

Context and Description of Initial Reform Plan

The reform project took place in the School of Electrical and Computer Engineering (ECE) at Oklahoma State University (OSU). OSU is a comprehensive, land grant, research university with multiple campuses; the reform project took place at the main Stillwater campus. ECE is one of six engineering schools in the College of Engineering, Architecture, and Technology (CEAT). During the grant period ECE had approximately twenty five tenure-track faculty members; many faculty were hired in the last decade due to a conscious effort to expand the engineering college. During the project period the computer engineering became separately accredited as a degree program. The student demographics are predominately traditional students who come both from the two urban centers in Oklahoma as well as many small, rural towns. Most students are Oklahoma residents.

From a high of nearly 500 undergraduate students in 2002, enrollment in the program fell, then rebounded to about 300 as of early 2010; enrollment has dropped in many ECE degree programs nationwide. Most attrition from the program is in the freshman and sophomore years. The engineering degree program is divided into two phases: pre-professional school in the first two years and professional school in the third and fourth years. Technically, students are not members of the department before they enter professional school. The mean time to graduation is between nine and ten semesters, reflecting the fact many students work while in college. Pre-professional school courses generally focus on math, science, and engineering science, are taught in large enrollment traditional lecture formats, and are taken by most engineering students. Professional school courses are more discipline specific, and taught within the department. The junior year courses form a “common core” taken by all students, while in the senior year student take guided electives in five “areas of specialization”: power and energy, computer engineering, solid state devices, signals and systems, and electromagnetics and photonics.

The project begun in 2003, when the program was awarded a DLR planning grant. Since the engineering faculty were not then conversant in education, the project included a faculty member from OSU’s college of education and another faculty member from the OSU library who would manage dissemination. During the planning phase, trial implementations of reform were made in four courses and participants met several times a month to brainstorm about needed changes. Much of the discussion in these meetings focused on ways to move the emphasis of courses away from “shallow” or “artificial” learning to support “deep” or “authentic” learning as discussed in (McClymer and Knoles 1992). The terms “shallow”, “artificial”, “deep”, and “authentic” were vivid and were clear to engineering faculty, who were often put off by technical education terminology. These terms are not generally well accepted definitions in engineering education, however. Shallow or artificial learning refers to students’ use of strategies like pattern matching or memorization to pass a class with as high a grade as possible, usually successfully. Such learning is reflected in an inability to transfer (Bjork 1994) learning and poor recall. Shallow learning is also restricted to a few types of knowledge (Krathwohl 2002), mainly factual and procedural, and is evidenced by students who have difficulty placing their work in a broader context. The planning phase hypothesized that making learning more relevant to students would improve learning outcomes since students’ perceptions of “artificial” were reinforced by test or homework problems that failed to address skills students believed engineers needed. In contrast, authentic learning sets tasks for students that mimic those used by practicing engineers, contextualize knowledge, and help students see how what is learned can be used in different contexts to support transfer. Participants generally agreed that in order to develop deep learning students needed to be given authentic tasks. In other words, to *become* engineers students need to continually practice *being* engineers. Authentic tasks may take students outside their comfort zone and demand extra effort, thus problems or projects should match students preconceptions of engineering work (see Figure 1).

These almost Zen-like statements were not easy to put into effective practice. A key lesson from the planning phase was that students, like Aeneas and all those who seek wisdom, make potentially perilous journeys: “*The way downward is easy from Avernus. Black Dis’s door stands open night and day. But to retrace your steps to heaven’s air, there is the trouble, there is the toil.*” (Virgil 1990). Authentic projects have a non-negligible risk of failure, potentially lure students into blind alleys, and may require tacit knowledge students don't possess (Collins 2001). Developmentally-oriented classes in ES21C were thus supposed to incorporate a significant amount of student support to avoid some of the pitfalls often associated with simply assigning projects. A key result from the planning phase was the need to provide security and assurance for students.

By the end of the two year planning phase, the vision described in the previous section had taken shape. The consensus of participants was that in order to successfully solve authentic problems, students need to both learn requisite knowledge and skills and be explicitly taught the *process* of solving the problem. Teaching the process of solving problems requires that faculty address different forms of knowledge and a range of cognitive processes (Krathwohl 2002) in their course. Memorizing Ohm's Law, for example, represents a different type of learning than being able to measure V, I, or R and a different cognitive process level than analyzing how a circuit will behave as voltage increases. Faculty thus need to identify the types and levels of learning that match course goals, ensure students have or are explicitly taught necessary skills, and finally adopt pedagogies that support this type and level of learning. To address a wide range of knowledge Bloom's Taxonomy was adopted as a guide for the reform project; the difficulties encountered and development of an engineering taxonomy will be discussed subsequently.

Engineering Students for the 21st Century's Strategic Approach

As discussed above, ES21C is transitioning a set of courses in the curriculum from a knowledge-based paradigm (acquiring a set of concepts) to being development-based (emphasizing students' development) to create a more effective, engaged, and efficient program. ES21C hypothesizes that a development-based program will produce more effective engineers by teaching students to use a broad range of knowledge in the context of solving engineering problems. Since students have the opportunity to experience a range of skills, they can identify roles that mesh with their personal goals, needs, and interests and become more engaged in their studies. Efficiency—effective use of both institutional and human resources—arises by aligning the undergraduate degree with faculty research to better engage graduate students in teaching and centralizing lab facilities as discussed later.

The original plan for program reform focused on two overarching goals which still guide ES21C:

- Increasing the depth of student learning by restructuring ten courses in the electrical engineering program to focus on student development.
- Redefining the role of faculty by engaging both current and future faculty in integrating scholarship back into teaching.

These two goals are obviously intertwined and synergistic; one is not possible without the other. The initial reform plan was to pursue both goals simultaneously. The second goal requires cultural change, however, and has been much slower to achieve and evaluate. This paper thus focuses primarily on the first goal since implementation was (relatively) straightforward due to the measurable, concrete outcome. Progress towards the second goal is addressed briefly throughout the paper. One key step made to date in achieving the second goal was establishing a university-wide certificate program for graduate students and postdoctoral fellows focusing on faculty preparation with an apprenticeship component. This program has allowed graduate students to become more engaged in teaching and able to support faculty in the reform efforts. A significant effort was also aimed at faculty development by supporting workshops and travel.

The strategy adopted by ES21C was to focus reform efforts on individual, stand-alone courses rather than an entire curriculum to make the reform more sustainable if faculty changed. The planning phase of the project showed that a rigid, prescriptive model would not be adopted due to the range of faculty beliefs about effective teaching. To balance the need to accommodate a range of faculty beliefs with coherence of the reform program, developmental courses share a common structure, or strategy. A common strategy was felt to be vital (Felder, et al. 2000) since an uncoordinated set of teaching methods forces students to continually adapt to changing expectations (National Research Council 2000). The strategy was guided by Bloom's Taxonomy (Krathwohl 2002), as discussed later. It should be noted the Bloom's Taxonomy is *not* a model of student development, but rather a tool that permits faculty to choose appropriate learning outcomes for their course and students.

The original plan for choosing the courses was based on two broad groups that faculty felt were critical to student development: applying mathematics to engineering problems, and system integration. At the time of the award, approximately 40% of engineering students made a failing grade or withdrew from the introductory calculus course and faculty cited mathematics as the major shortfall of student preparation. A review of curricula indicated OSU students spent less time on systems engineering compared to peer universities. The courses reformed are shown in the table below with the program year, and the period in which active reform occurred. Note that since students take, on average, nine to ten semesters to graduate but the degree program is officially eight semesters, students get out of synch with each other. Thus some courses are listed in two different program years. Two of the courses that were initially slated for reform did not get reformed, represented by "NA" in the table below. The course *Engineering Your Future* encountered numerous obstacles, and despite significant efforts and investment the course never converged into a teachable format. This was a significant setback, and many of the elements originally scheduled for this course were later implemented in *Applying Mathematics to Engineering Design*. *Networks and Linear Systems* was almost fully developed when the faculty member in charge of the course moved to another university. His untenured replacement did not feel that course reform was in his best interests in

Program Year	Reform Period	Course and Description
Fr.	2007–2010	*Applying Mathematics to Engineering Design:* Teaches how mathematics is used in the engineering design cycle (M)
Fr.	NA	*Engineering Your Future:* Teaches students to prepare portfolios, how to monitor their development, and teach skills in teamwork and peer evaluation.
Fr.	2010	*Introduction to Engineering:* Introductory course mainly focusing on retention, but also has elements of ethics and design.
So.	2005	*Electrical Science:* Basic circuits course for all engineers (S).
So.	2010	*Experimental Methods:* Teaches basic electronic measurement techniques and principles of system design (S).
So./Jr.	2004	*Introduction to Digital Logic Design* discrete and field programmable gate array logic devices (S).
So./Jr.	2006–2008	*Semiconductor Device Physics for Engineers:* Physics of semiconductor devices (M).
So./Jr.	2007–2009	*Microcomputer Architecture:* Basic architecture, I/O. and programming of embedded microcontrollers (S).
Jr.	2003–2006	*Electromagnetic Fields:* The standard EM fields course covering electro- and magneto-statics and plane waves (M).
Jr.	NA	*Networks and Linear Systems:* This course teaches the basics of linear system theory relying heavily on application of mathematics (M,S).
Jr./Sr.	2003	Engineering Optics*: Optical system design for engineers (S)
Sr.	2005–2007	Laser Electronics*: Course focusing on laser design and modeling as an example of complex, tightly coupled systems (S).
Sr.	2007	Microwave Systems*: Design of high frequency devices and systems. Students design and build a synthetic aperture radar (S).
Sr.	2005–2010	*Design of Engineering Systems:* Teaches engineering design from a systems perspective through team projects (S).
Sr.	2006–2008	*Senior Design:* Teams of students undertake independent design projects under guidance of a faculty mentor (S).

Table 1: Engineering Students for the 21st Century Courses.

the first years of his career. As the reform project winds down, two new courses are under development, an introductory course in the freshman year and an experimental methods course taken in the sophomore year. Although not anticipated in the initial planning, three elective courses (*) are also incorporating the ES21C format.

The strategic approach planned for ES21C courses was to first structure learning around two or three fundamental problems or projects rather than a list of topics or needed content. To pose the fundamental problems in a relevant context, each project begins with a case study or other means of contextualizing course material. Preparing a conceptual foundation and teaching students the process of solving the problem occurs in three parallel steps based on the cognitive process dimension of Bloom's Taxonomy (Krathwohl 2002): (1) remember and understand concepts needed in solving the problem *outside* of the classroom; (2) during class student teams apply what they know and analyze the problem using active learning; (3) outside class (typically in a lab) student teams create a solution to the problem through a design project then evaluate how well it works. To support teamwork, ES21C developed resources for team building and peer feedback; these are discussed later. At the end of each project, teams communicate what they have learned, ideally by creating an engineering portfolio. Each class was also supposed to integrate reflective activities to help students learn from their experiences, both good and bad. These features (strategies) guided the curriculum reform strategy, but individual faculty were free to choose techniques (tactics) that best suit their teaching style, course goals, and the level of their students.

Educational Basis of Engineering Students for the 21st Century

The *Engineering Students for the 21st Century* reform vision outlined above seems simple at first glance, but has at its core several fundamental beliefs that run counter to current practice and the beliefs of some faculty:

- Contextualizing learning around projects implies that learning goals are determined by the project as much or more than some external set of facts, concepts or topics such as those found in a textbook. If some subset of factual, conceptual, or procedural knowledge is not needed to complete the project it need not be taught.
- ES21C recognizes that learning is developed over time, is based on an individual's prior knowledge and experience, and has hysteresis; reform tries to create a "knowledge-centered environment" (National Research Council 2000) in courses. Thus different students may draw different lessons from a class; in ES21C this is expected and desirable.
- Since development is incremental and individual, students' paths may diverge throughout their degree program as they develop into creative and innovative engineers. Graduates should be prepared to go on to diverse careers, even if these are not in engineering.

Given ES21C's non-traditional assumptions, this section briefly outlines the basis in learning theory for key elements of ES21C courses.

Structuring courses around problems is drawn from Problem-Based Learning (PBL) (Barrows and Tamblyn 1980; Woods 1996). In ES21C, PBL takes place in three steps to teach the process of problem solving. First, course work is contextualized around the problem allowing students to determine if what they learn applies to their project, developing metacognition (National Research Council 2000). Second, students implement a solution to the problem as part of a team; implementation presents students with ill-defined problems (PBL website 2002, National Research Council 2000) that support transfer of learning (Bjork 1994). Third, students evaluate then report on their team's implementation, often by creating a datasheet. Quantifying the project's performance helps students see the utility of course content. These steps are described in more detail in the following paragraphs.

The first step, creating context, allows students to make connections between what they know, transfer that knowledge to new situations, and continually practice these skills- hallmarks of deep learning. Such interconnections and transfer occur more easily if a student has a framework or "scaffold" on which to attach new knowledge (National Research Council 2000). All students have such scaffolds that are built from prior experiences; since all students are unique individuals with different experiences, each scaffold is different. It is virtually impossible for faculty to know students' preconceptions, and difficult to correct misconceptions that occur when students learn wrong information or transfer knowledge to an inappropriate context (Burbules and Linn 1992).

ES21C courses create scaffolds by introducing projects through a case study. Case studies provide intent (Minniger 1984) (i.e. the student knows the knowledge will be used), makes knowledge relevant (McCombs 1996; Pintrich and Schunk 1996), and places work in a context related to students' prior experiences. Placing knowledge in context (Glaser 1992) enhances transfer (National Research Council 2000; Gick and Holyoak 1983). The case study explicitly asks students to self-identify personal learning goals for the course. In-class discussion of the case study also helps define the problem in terms of familiar schemas (McVee, et al. 2005); being able to think in terms of schemas is one characteristic of an expert. For example, an electrical engineer can look at a large circuit schematic and identify groups of individual components as functional elements, dramatically simplifying overall conception of the circuit's function. Since students in a class do not have the same schemas, in-class discussion of the case study allows students to recognize differences between their individual schemas, develop a group schema for the project, and identify areas in which they have low proficiency. Case studies let students utilize experiential or narrative (Epstein 1994) modes of processing information rather than the academic language so often used in traditional courses (Gee 2004). Using a case study before teaching concepts improves learning more than using it afterwards (Lundeberg and Schuerman 1997). In the planning phase of the project students' self-reports of learning gains showed that the case study was rated as having the largest positive impact on learning.

The second step in ES21C's implementation of PBL is to have students solve the problem posed in the case study. Contextualizing classes around a project requires that the classroom experience be transformed to allow the instructor to focus on the process of solving problems rather than transmitting knowledge. ES21C accomplishes this by first classifying course content using the taxonomy described in the next section. Students acquire information (*understand* cognitive process level) outside the classroom, address apply and analyze processes in the classroom, and develop design skills through building the project. Thus, while traditional courses transmit content in class and assign problems to be done outside of class, in ES21C this model is flipped and information is acquired outside of class and problems are done in class. To facilitate learning, the instructor needs to provide resources that help students acquire information; examples include short videos (Cheville 2009d, hyperlink), web sites, and readings from the textbook. In putting the onus of knowledge acquisition on students it is important to provide formative evaluation—feedback during learning—quickly enough so that students can correct their misconceptions and develop metacognition (Ericsson, et al. 1993). New technologies such as course management systems and on-line Java applets support such formative evaluation.

While students can learn lower cognitive process levels of the taxonomy outside of the classroom, higher levels are addressed by active learning in class, often using teams. Active learning simply means students are active participants in the class rather than passive listeners (Smith et al. 2005). A significant body of research has shown that in well-organized classes active learning gives rise to significant improvements in performance (Schwartz et al. 1999; Froyd 2007). Active learning helps change students' perception that the instructor is responsible for learning. In ES21C, active learning is framed in the context of the problem addressed in the case study and project and provides students information needed to complete their project. The instructor should inform students of how learned knowledge applies to the project and be integrated with learning from previous classes to develop near transfer (Alkon 1982; Druckman and Bjork 1991). Transfer—the ability to take what has been learned in one context, and extend it to a different context—is a key ability in "problem solving" (Jonassen 2000), a skill that faculty in our program value. Active learning connects the material read outside of class to the project that scaffolds the class.

The project is done outside of the class time, typically in a laboratory environment, although some instructors have used take-home kits. In some ES21C classes parts of the project are done as active learning in class and teams simply need to integrate work they have already performed in completing the project. A project should be involved enough that it is too complex for one individual and extend over several weeks at a minimum (Smith et al. 2005). Teams, when properly implemented, improve learning outcomes (Smith et al. 2005) and allow more authentic (and interesting!) problems to be assigned. Having students work in cooperative teams has been shown to benefit non-traditional students and women (Seymour and Hewitt 1994). ES21C has also developed a peer feedback system to help students learn from team experiences; this is discussed subsequently.

The third step in ES21C's implementation of PBL is for students to report on the results of the team project. Reports include both team and individual contributions; individual writing assignments ask students to self-explain (Chi et al. 1994) and reflect on the learning experience. A large fraction of students' grade (50% in some courses) is based on communicating the results of technical work to help ensure students take reporting seriously.

CHANGES ENGENDERED

The previous sections described the vision, history, and strategy of *Engineering Students for the 21st Century*, and discussed the project's basis in learning theory. Since ES21C seeks reform at the department level, the project is also changing the learning environment. This section first outlines ongoing changes to the learning environment with an emphasis on tools that can be adopted by others. Next, four short case studies illustrate how the ES21C model and changes to the learning environment reformed select classes.

ES21C has engendered several substantial changes and improvements to the resources available to faculty across the program to support learning. As discussed previously, a key element of ES21C is classifying learning using a taxonomy to help determine what aspects can be pursued independently by students outside of class, and which should be addressed by projects or active learning in class. Initially ES21C used Bloom's Taxonomy, but this was quickly found to be too general for most faculty to use successfully without a significant time investment (Abe and Starr, 2004). To better understand and classify learning, an engineering taxonomy was developed. Bloom's Taxonomy has previously been adapted to measure ABET outcomes in engineering programs by addressing each of ABET's (a)-(k) outcomes (ABET 2008) on seven cognitive process levels (Besterfield-Sacre et al. 2000). While this taxonomy directly assigns levels of ability to the requisite ABET outcomes, comprehensiveness comes at the cost of complexity. In creating an engineering taxonomy for ES21C, the cognitive process dimension of Bloom's Taxonomy was reduced from six to four elements. On the knowledge dimension factual and conceptual dimensions were retained unchanged and the process dimension included five aspects corresponding to sequential steps in the engineering design process developed for ES21C: researching, modeling, implementing, measuring, and communicating (see Figure 3). The expansion of the process dimension reflects the importance ES21C places on design (Sheppard et al. 2008). A short version of the design taxonomy focusing only on process skills is shown in Figure 2; a complete version can be downloaded from the ES21C website (Cheville 2009a, hyperlink). Compared to design cycles published in texts on design (Ford and Coulston 2007) ES21C developed a simplified cycle with fewer steps, Figure 3, to simplify classification of course activities and eliminate design process steps that posit high-level thinking skills which could invalidate the taxonomy.

To better understand students' learning experiences, a survey based on the engineering taxonomy was developed and given to faculty in the ECE department in 2007 (Cheville, et al. 2008). For each element of the taxonomy (cell on the table in Figure 2), the survey asked faculty to report how much impact work of that type (i.e. understand modeling) had on the overall course grade. Faculty members were also asked to rate the relative importance of each element of the

Cognitive Process Dimension

Knowledge Dimension

	Understanding: being able to recall what you learn and define, explain or give examples to others.	**Applying:** using information to accomplish something concrete.	**Analyzing:** being able to extract meaning from a collection of information.	**Designing:** creating something new under constraints to achieve a near optimal outcome.
Research Learning about a problem before you solve it .	Explain a problem in your own words, find information needed to solve the problem, and determine what you need to know to solve the problem	Fnd and use information needed to solve a problem from textbooks, on-line resources, or other technical sources.	Select and filter your results to find information that is useful in solving a problem.	Use the results of research to select a productive approach and implement a specific plan of action.
Model Using mathematics to understand and make predictions about system performance.	Solve and graph single equation models and identify the conditions under which the solution applies	Compute or solve a mathematical model of a physical system and plot the behavior of the system either analytically or computationally.	Perform calculations which predict performance of a device or system and test/validate these predictions.	Optimize the performance of your model and use an engineering model to make design decisions.
Implement Going from ideas, models, or concepts to a physical realization of your design.	Explain how to turn the design into an actual physical object if you are given standard engineering drawings or diagrams.	Build a simple engineering device, follow a process, or write code using appropriate tools and techniques	Select between different fabrication techniques and select appropriate parts or materials given project constraints.	Construct a device with multiple, interconnected systems in an efficient, affordable way that meets external constraints.
Test Determining how well a system or device functions by performing measurements.	Identify the correct measurement instruments for a task and write down the procedure for taking a measurement correctly.	Take valid measurements using instruments and record the data in a format that can be shared with others.	Use data you to determine if a device is functioning to a given specification or a process meets external requirements.	Choose or create correct measurement techniques, acquire interpret data, and then use this information to make design decisions or determine if a device meets specifications.
Communicate Expressing results of work so others can understand, reproduce, and improve it.	Identify appropriate formats and styles for your technical communications as well as what information will be communicated for each format.	Present evidence to an audience at a level they can understand either in writing, through oral presentations, or at a meeting.	Edit your own work or the work of others for style and content to meet the needs of a particular audience.	Create a well-reasoned, data-driven argument or presentation either from your own work or from work that others have done.

Figure 2. The process portion of the ES21C engineering taxonomy. The complete taxonomy, guides on using the taxonomy, and support software can be found at this hyperlink

cognitive process and knowledge dimensions to their course outcomes on a five element Likert scale. "Researching" was the aspect least reflected in student work, particularly in the sophomore and junior years. Faculty also reported that "communicating" had little impact on grades despite the fact faculty reported this as an important skill. Faculty reported students performed the most work on conceptual knowledge and modeling/calculating. The development of an engineering taxonomy has given ES21C a means both of classifying student learning to determine which activities are appropriate for different pedagogies, but also a way to measure changes in what students learn over time. A complete description of the Engineering Taxonomy and survey development has been submitted for publication to *Advances in Engineering Education*.

Another tool developed under ES21C was a flexible method of supporting peer evaluation in team experiences. As mentioned previously, team work is an integral element of the ES21C model. During the project a web-based peer evaluation system was developed both to collect data on team

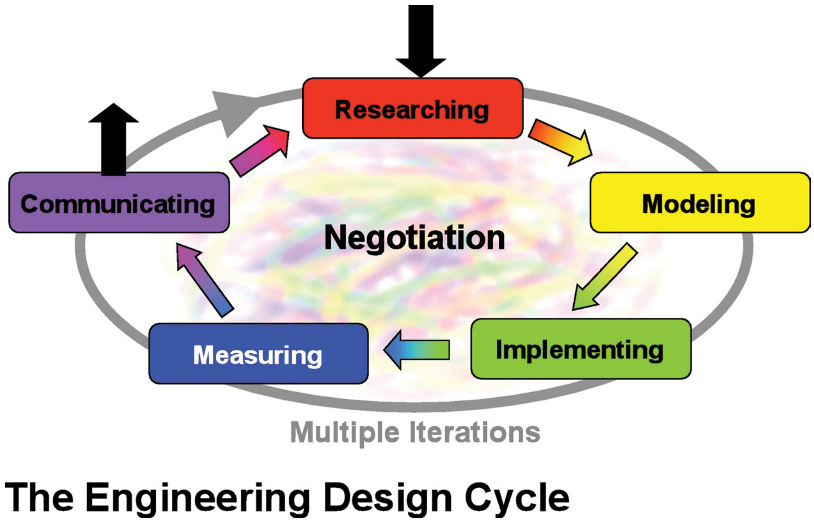

Figure 3. The ES21C engineering design cycle the program is using to frame design classes and which define the process elements on the engineering taxonomy (Figure 2).

performance and provide feedback to students on their performance on the team. While other peer evaluations exist (Ohland 2009), the ES21C-developed system—the *Simple Team Experience Assessment Measure*, or STEAM—is highly configurable by the instructor to meet the specific needs of their class. Five different evaluation tools can be fully configured by the instructor: a Likert (1-5) scale rating of team member attitude and value, numeric reporting by peers on the perceived work put forth by team members, a survey designed to measure a team member's effectiveness, anonymous text feedback, and an overall rating. Almost any combination of tools may be configured depending on the needs of the class. STEAM has been used in several classes to evaluate changes to student learning and their effectiveness on teams; for more information consult (Cheville, et al. 2007; Cheville and Duvall 2008) or to use STEAM visit the peer evaluation web site (Cheville and Duvall 2009, hyperlink to STEAM site). An on-line electronic contract that allows students to specify their own roles and tasks and then be evaluated on meeting the terms of the contract at the end of the project is in beta test phase; if interested please contact the lead author.

Engineering Students for the 21st Century is also changing the departmental infrastructure to better support projects and empower engineering students to explore all aspects of engineering design by slowly transitioning away from the model of a pre-configured lab bench. Using commercially available electronic catalog software, students or teams can check out instrumentation from a department web site to use over the course of the semester. By checking out equipment, students are responsible for the equipment and can access lab facilities on a 24/7 basis. Three different catalog systems (Cheville 2009a) support different aspects of learning: one is to check out equipment that will be returned, a second lets students purchase expendables such as electronic components, and the third is used to sell kits developed under ES21C. To teach the actual cost of engineering projects, electronic equipment is priced at actual cost, however the equipment is loaned to students rather than purchased. The catalog helps develop student discernment in lab equipment selection without the need to teach extra content on laboratory instrumentation since students must exercise judgment in choosing appropriate instrumentation, and also build their own test and measurement systems to meet team needs. The rate of broken and damaged equipment has been reduced since students take better care of equipment they are personally responsible for.

Since the challenges and triumphs of an undertaking the size of department-level reform are impossible to fully document in a single article, an overview of how ES21C was implemented in four courses follows. These short case studies of successfully reformed classes cover the spectrum from freshman to senior, theory to application, and purely electrical engineering to multi-disciplinary service course. Each case outlines the changes that were made to the course, and briefly reports evaluation results. Where available, references are made to publications that present more details.

Case Study #1: Electric Circuits (ENSC2613)

Like many engineering schools, a wide range of students take a requisite engineering science course in electric circuits, part of the pre-engineering curriculum. Classes are large, typically around 200 students. While for electrical engineers the course is a critical prerequisite and taken in the sophomore year, students in other majors may delay taking the course until they are seniors. ENSC2613 was one of the first courses reformed under ES21C; the course was improved over several iterations and has currently reached a steady state.

Before the changes made under ES21C, the course was taught in a traditional format with several lectures per week and regular summative homework assignments and tests. Since course content is determined by an interdisciplinary faculty committee, there were few changes to the content. To show the impact of ES21C, the instructor chose to adopt an ABAB model where “A” corresponds to a nominally four week period of lecture and summative assessment and “B” to four weeks of the ES21C model outlined previously. The only changes to the ES21C model outlined previously were reducing the scope of the projects, giving teams a written case study rather than active discussion in class, and changing the format of in-class active learning. Due to the large size and diversity of the class in-depth projects were not feasible, so the instructor chose to implement a series of shorter team projects. Projects were introduced through a short case study that discussed a problem at an engineering firm. In-class active learning consisted both of traditional written problems as well as measurement challenges using a project kit provided to each team; kits contained a protoboard, components, batteries, and digital multimeter. Selected teams demonstrated their solutions in class on a computer with data acquisition and virtual instruments running in LabVIEW® so results could be shared with the class.

Initially the ABAB structure was done as part of a research study to assess the impact of ES21C on student learning. After the end of the study the instructor chose to continue the ABAB model since he believed students with different learning styles benefitted from experiencing different pedagogies; the accuracy of this belief has not been verified experimentally. The instructor reported there was initially considerable "push-back" from students who felt they were not being "taught" since the role of the instructor is less active under ES21C. This attitude has decreased with subsequent iterations as ways have been found to inform students that the course closely mimics engineering practice. Over time, the instructor has made increasing use of the engineering taxonomy (Cheville, et al. 2008) to ensure out-of-class work addresses appropriate cognitive process levels.

Learning in ENSC2613 is being evaluated using a Student Assessment of Learning Gains (SALG) (SALG Website 2009), summative case analysis tests (Lundeberg and Schuerman 1997), and short assessment questions posed as part of each project report. Initial analysis of SALG results show there is quite a wide range of student opinion about the course; some students report they are not being taught while others embrace the more proactive approach to learning. The case analysis tests, done in a pre-post format for each part of the ABAB research design, show greater learning gains on the ES21C-taught B units, but also significantly larger standard deviation. This is consistent with SALG results if there is a group of students who disengage from the course. The instructor, who has significant prior experience teaching using the ES12C format, has reported differences in the pace at which students learn in the A vs. the B units. In the more traditional A approach there is little apparent effort by students until just before homework is due at which time there is a large spike in student effort. Under the ES21C model, a more moderate pace of work occurs throughout the entire week. Overall the instructor reports "enrichment" of the learning environment with less opportunities for students to "slip under water", i.e. drop out of the course with little prior notice. The instructor's awareness of student status increased significantly after peer evaluations were introduced. A more complete description of changes to learning can be found in (Yadav, et al., 2011).

Case Study #2: Design of Engineering Systems (ECEN4013)

As with most engineering programs, ECE students undertake a capstone design experience in their final year; ECE requires two sequential capstone courses. For many students the capstone course fit Sigmund Freud's definition of experience: *"Experience is what you get when you* *experience what you do not wish to experience."* The first course, described here, prepares students for independent, team-based design projects in the second course. Prior to the start of ES21C, the first capstone course consisted of a series of tightly constrained electronic design projects performed by individual students. Grades were determined by quantitative performance metrics (i.e. signal to noise ratio, accuracy of gain, etc.). A survey of students who had completed the course showed students felt fundamentally unprepared for the design experience. A representative comment was "*…all of the undergraduate level courses did not build up to this course. This was like 'wanting to fly without even knowing how to crawl'*".

Early in the course reform process, faculty realized that the course was too focused on completing projects without having identified clear and teachable learning goals, resulting in a highly variable rate of project success. The ES21C model provided guidance on effective pedagogy while learning goals were identified. Key elements drawn from ES21C were the focus on projects, communication, active learning, and working in teams. Action research (Bodner and Orgill 2007) was then used to develop and implement learning goals in engineering design that were relevant to students. The instructor first set initial learning objectives, engaged stakeholders—including students, alumni, faculty, and the advisory board—in identifying most and least effective practices, and then iteratively made changes to the course. From this process several key learning objectives emerged: teaching design as a process, ensuring students gain experience at each process step, teaching elements of project management, and ensuring each student had a meaningful role on design teams that included individual accountability (Cheville, et al. 2007; Cheville and Duvall 2008; Co, et al. 2007).

Even more than other ES21C courses, the project forms the central core of ECEN4013, contextualizing all learning. Students meet in class weekly to learn project management skills through active learning. The majority of student time is spent in the lab which consists of a five week training project, a nine week design project, and a week of reflection and reporting. The training project teaches elements of electronic device fabrication that are not covered earlier in the curriculum, ensuring each team member can contribute meaningfully to projects. Students learn fabrication, programming, or test and measurement skills and then apply these skills to fabricate a working electronic device from a schematic diagram as part of a team. The electronic peer evaluation instrument discussed previously (Cheville and Duvall 2009) is used to accelerate team development (Smith et al. 2005). The design project follows the five step design process developed as part of ES21C (Figure 3). At each step students must demonstrate a minimum level of competence to advance to the next stage of the design cycle. The last week of the course is devoted to reflection and reporting to give students experience in technical communication and reflect on how the experience was transformative.

Since the capstone course sequence is critical to ABET program evaluation, a significant effort has been made to assess course outcomes. Both qualitative and quantitative metrics paint a picture of students gaining a realistic perspective on the social process of engineering design, including the uncertainty of the process, importance of broad technical expertise, and need for negotiation and compromise (Bucciarelli 1994). It is clear from qualitative evaluation of reflective statements that students' experiences vary greatly depending on the roles they take on and their level of engagement. The observation that learning is dependent on a student's goals reflects one of the fundamental assumptions underlying ES21C's overarching goals as discussed previously on the section on ES21C's basis in learning theory. More details on the specific implementation, theoretical foundation, and evaluation of this course can be found in (Cheville 2010).

Case Study #3: Semiconductor Device Physics (PHYS3233)

A required course taken late in the sophomore year or early in the junior year, PHYS3323 has a convoluted history. Well before the start of ES21C students took engineering science courses on fluid dynamics and strength of materials. Since ECE faculty felt these courses did not support other courses in the curriculum, a survey course in modern physics was substituted. Later, program evaluation showed that the modern physics course content varied greatly depending on the instructor, and that students thought the content was not germane to electrical engineering. Faculty in ECE then worked with colleagues in Physics to develop a course in semiconductor device physics that covered the basics of modern and solid-state physics, semiconductor materials, and the PN junction. A veteran instructor taught the course in a traditional lecture-homework-summative exam format for several years before the start of ES21C. The instructor was very interested in course reform since he reported that while students made acceptable grades on procedural problems, they lacked conceptual understanding.

Attempts to reform the course at the beginning of the project faltered since the pedagogies called for in ES21C were unfamiliar to the instructor and TA's in the Physics department. As the project progressed, a team consisting of graduate students and faculty in ECE and Physics made a second, successful attempt at course reform. In the spring semester of 2008 a trial run at a reformed course model was made in a ABA format; approximately five weeks of an ES21C model was taught first (A), followed by traditional lecture (B), and concluding the course with the ES21C model. This preliminary implementation gave only anecdotal evidence of a positive impact on learning. Students self-reported better understanding of topics and performed better on problems on the portions of the final summative examination that were taught using the ES21C model compared to the traditional lecture style.

At the end of the spring semester the original instructor announced he would retire, and a new physics faculty member agreed to teach the course in Fall, 2008. The new instructor was initially highly skeptical that the active learning approach used in ES21C would allow students to learn the highly conceptual and emergent (Chi 2005) material covered in this course. Thus in the summer of 2008 the two physics faculty and the PI of ES21C worked with graduate students to complete the course reform and address the new instructor's concerns. The content was reorganized into seven modular units, each organized around an engineering-related context. The course begins by explaining how night vision goggles work by introducing uncertainty and the photoelectric effect and ends with PN junction diodes. Each unit follows a three-step timeline. The first day reviews learning objectives and outlines major concepts of the unit using lecture. In the middle portion of the unit readings drawn from the textbook, web sites with illustrative JAVA applets, and other sources are assigned before class. To ensure students have a basic understanding of course material, a formative on-line quiz is given over each reading. To prepare students for active learning exercises done as team in class, they are given the in-class exercise (ICE) before class with all numeric data blacked out. At the start of class each student turns in a written *strategy* for solving the ICE in the form of pseudocode or a flowchart. This prequel familiarizes students with the problem and helps ensure students do not spend class time familiarizing themselves with the problem. The complete ICE is then solved by teams of students in class. The instructor circulates throughout the room assisting students or giving short explanatory lectures as needed. The final day of the unit serves as a review and wrap-up. The formative quiz for the review day consists of conceptual, multiple choice questions reviewing module topics and an on-line forum where students submit questions; questions are reviewed and graded by the instructor. In the classroom the instructor answers student-submitted questions and corrects misconceptions about the unit. The one exception to this format is the "crystal zoo" module which, due to content, is taught using traditional lecture.

Content was developed at weekly meetings in summer 2008 that involved the three faculty and graduate students. Over the first month progress was slow as participants became familiar with ES21C pedagogy and how it was applied in the classroom. Over time, each faculty member took on the role of an expert in some aspect of course development. The new physics instructor had clear learning and content goals and a deep understanding of device physics, his research area. The outgoing physics instructor had years of experience with students' conceptual difficulties and prior preparation and knowledge. The engineering faculty member provided expertise on pedagogical techniques and was able to contextualize content so it was relevant to engineering students. Once roles were established, course development proceeded rapidly through the summer and at bi-weekly meetings during the fall semester.

As mentioned previously, the instructor who took over the course in fall 2008 was deeply skeptical that the active learning approach would be effective for the conceptually difficult material covered in PHYS3233. Over the course of the semester his attitude underwent a 180° shift. Despite some disengaged students, overall both teams and individual students performed well on assignments and exams. Class attendance and engagement were higher on active learning than lecture days and the instructor received a great deal of feedback on student learning at the end of module question session and by monitoring team progress during ICEs. Overall course grades were quite high, with non-engaged students doing significantly more poorly than peers. These experiences mirrored those of the previous physics instructor in the Spring 2008 trial. Students self-reported high learning gains and high satisfaction in the end-of-semester SALG (SALG Website 2009) that was developed for the course.

Case Study #4: Engineering Mathematics with Design (ENGR1113)

OSU students take a two year "pre-professional" course sequence common to all engineering students before admission into one of six engineering professional schools (departments). From a logistics viewpoint, the first two years of the program turned out to be more difficult to reform since change impacts students outside the electrical and computer engineering department and thus requires consent from a large number of stakeholders.

ENGR1113 is a three credit hour course (standard at OSU) taken in the first semester of the freshman year and reform was undertaken fairly recently. The three credit hour course was created by removing two introductory engineering courses; ENGR1113 retained critical elements of these courses. The course introduces students to engineering through design projects in which they apply mathematics and learn the five-step ES21C design cycle, Figure 3. ENGR1113 is loosely modeled on previous efforts at Wright State University (Klingbeil 2005) to improve retention by illustrating mathematics in engineering, but additionally introduces design using the ES21C design cycle. The course follows the ES21C model by integrating case studies, projects, written communication, reading outside of class, formative on-line quizzes, and having students work in teams.

The class meets three times per week. Projects are introduced on Thursdays and all projects are contextualized around real-world applications. For example, a project illustrating linear algebra discussed mixing syrups and carbonated water for soft drinks as a chemical engineering process. Reading and formative on-line quizzes are assigned on a weekly basis and a recitation session helps students who need assistance understanding concepts. The on-line quiz prepares students for the Wednesday lab in which teams of three students take on six challenges throughout the course; each challenge has both engineering analysis and engineering design components, and each is contextualized around a real world problem. The six challenges have students apply algebra, linear algebra, trigonometry, sinusoids (waves), derivatives, and integrals. Lectures are given once a week to introduce new topics and illustrate application of mathematics to the engineering problem. Each lecture solves problems twice, once using an analytic approach then revisiting the problem and solving it numerically using Matlab. To report on their work, teams submit three written reports over the semester that are reviewed by peer writing coaches before final submission to allow feedback on writing performance. Individual students write reflective statements over topics in engineering, mathematics, and design; both reports and statements are graded using a rubric given to students.

Since ENGR1113 has only been offered once, evaluation of course outcomes are still preliminary. A pre-post attitude survey and pre-post mathematics concept inventory were given using a one hour introduction to engineering course as a control group (Oswald, et al., 2009). For the concept inventory both sample ($N = 37$) and control ($N = 32$) groups performed better on the post test, but the difference was not significant. The control group did significantly better on both pre- and post- tests than the sample group; the difference is likely due to self-selection since students who felt they needed help in mathematics were encouraged to enroll in ENGR1113 by counselors. On the mathematics portion of the ACT test, ENGR1113 students performed 1.4 points lower than the control group; the difference was not significant at $p < 0.2$. ENGR1113 students scored 1.2 points higher, however, on both reading and science reasoning ($p < 0.25$) The mathematics attitude survey asked about intrinsic motivation, preconceived notions about mathematics and engineering, and motivation to continue in mathematics. Analysis of variance showed that for all categories the control group had a significantly lower mean ($p < 0.05$) than the sample, indicating that the new course had a positive impact.

CHANGES IN STUDENT LEARNING

The goal of *Engineering Students for the 21st Century's* reform of department infrastructure and courses was to improve student learning. To understand changes to student learning, ES21C initially outlined four research questions focused on whether students learned "better" in reformed courses. As the project has evolved it has become increasingly clear that while the question "Are students learning better?" is often asked, the answer is almost always "It depends". A better question is "What are students learning?", which requires faculty to first clearly define what they want students to learn. Faculty often overlook the importance of identifying achievable learning goals, set goals that are not measureable, or focus exclusively on content to the exclusion of procedural skills and metacognition. Through ES21C the program has made progress identifying learning goals across the curriculum by working with faculty to write "Be Able To's" that define measurable outcomes for each class; this work is still ongoing. While much of the evaluation done under ES21C to date has been focused on courses, a holistic view of how ES21C has changed graduates' experiences is slowly emerging. This section discusses the progress that has been made to date in changing student learning and attitudes program-wide.

A variety of metrics are used to monitor student learning. Broad trends in student learning are measured through both quantitative and qualitative measures. To be able to sustain reform at the end of the funded phase of the project, these measures have been closely aligned with program and learning evaluation that is performed as part of the ABET CQI cycle, as will be discussed later.

One measure used to determine the impact of ES21C on students is a phone survey of undergraduate alumni who graduated one year and five years ago that is conducted by OSU every other year. While most survey questions have Likert-scale (1 = low, and 5 = high) responses, some open-ended questions are also asked. Survey responses from 2002 to 2008 (the last year data is available) were analyzed to determine changes in alumni's view of the program over the period ES21C was implemented. Results for two groups of questions are shown in Figure 4, the satisfaction students have with the program, and preparation in design and teamwork and communication. The five year alumni data are shown in blue while the one year alumni data are shown in red. Note that there are one and five year lags between survey data and when effects would be observed. Dashed arrows represent points in time alumni would first have experienced changes due to the initial planning phase of ES21C that started in 2003 and solid arrows represent full implementation in 2005. The five year alumni figures (shown in blue) generally lag those of the one year alumni (shown in red) which provides supporting evidence the changes are due to programmatic changes rather than changes to the survey methodology. The response rate varied between approximately 20% and 40% for the five year data, and 40% and 60% for the one year data, leading to sample sizes from N = 19 to N = 64 depending on the year the data was taken.

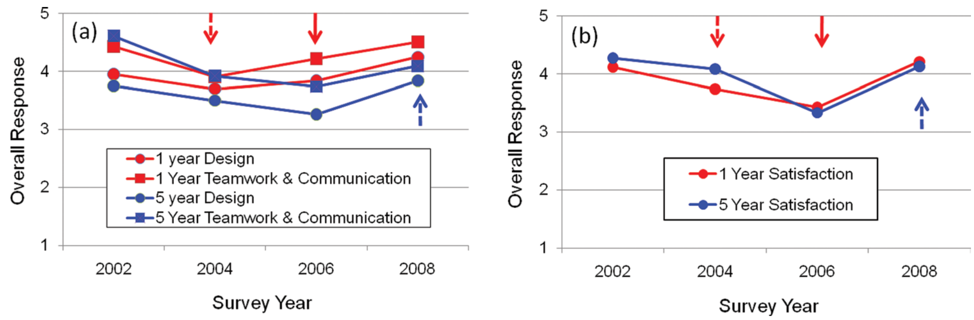

Figure 4. Responses to an alumni survey for alumni one year (red) and five years (blue) following graduation. The dashed arrows represents the first point in time alumni would be impacted by the planning phase of the project, and the solid arrows the full implementation. (a) shows design and teamwork & communication skills, while (b) is overall satisfaction with the program.

The data shown in Figure 4 is supported by qualitative, open-ended survey question responses. The number of alumni who cite design as a strength of the program in open-ended comments roughly doubled from 2002–2004 (pre ES21C) to 2006-2008 (post ES21C) from 20% to 40%. Note that there is no way to separate one-year and five-year graduates on open-ended responses, but the number of one-year respondents is larger. A similar magnitude drop was observed in the number of alumni who reported lack of design opportunities was a weakness. While not as dramatic, increases in alumni who report teamwork and communication as *both* a strength and a weakness of the program have increased. It is not clear why more alumni report that the program is getting better and needs to get better still. It may be that more alumni are aware of the importance of communication and teamwork skills in their engineering careers. While responses on design preparation and overall satisfaction with the program increased, there were not significant changes in alumni reports of preparation for graduate school, professional and community involvement, or preparation in social and economic aspects of engineering. The survey data provides indirect support that ES21C is having intended changes to program graduates. While other factors cannot be ruled out, there were no other major changes to the degree program during this time period.

To measure changes over time in student attitudes and beliefs, an exit survey is given to students just prior to graduation. All students are required to complete this survey leading to sample sizes (depending on semester and year) from N = 12 to N = 54. A group of questions on the survey asks students to self-report their perceived ability in multiple areas. While self-reporting of knowledge or ability may be suspect as objective data (Kruger and Dunning 1999), survey results are interpreted as relative changes in the perceived ability of student cohorts over time. Survey questions were grouped into five general categories: coursework, breadth, design, professional development, and context. The coursework category included seven questions covering students' ability in different courses required to earn a degree. This category was used as a control, since the questions focused on courses that did not participate in ES21C. There were four questions in the breadth category that focused on the extent or range of student abilities in experiments, systems, analysis, and design. The design category asked four questions on teamwork, communication, and perceived ability on design projects. Six questions in the professional development category focused on professional development and activities. The context category asked four questions about students' ability to place engineering work in societal, environmental, global, and economic contexts.

Seven years of survey results are shown in Figure 5(a); data was not collected the fall semester of 2003. The data has been normalized to the coursework responses and shows changes in the mean response over time. From the start of ES21C implementation in Fall 2005, students perceived they had a wider breadth of ability, which is expected based on the fact that ES21C attempted to expand the domains of engineering knowledge taught in the program. Students' self-perceived ability to contextualize engineering increased slightly, but gains in professional development, a goal of ES21C, did not occur. Surprisingly, was there little increase in self-perceived ability in design. When the design category was separated into components of teamwork, communication, and design, students' perceptions of their ability in design have begun to increase over time, while those in communication and teamwork did not change, as shown in Figure 5(b). Note that the relatively flat self-perceived abilities at graduation in communication and teamwork do not agree with the alumni survey data discussed earlier. It may be that students have difficulty self-judging their

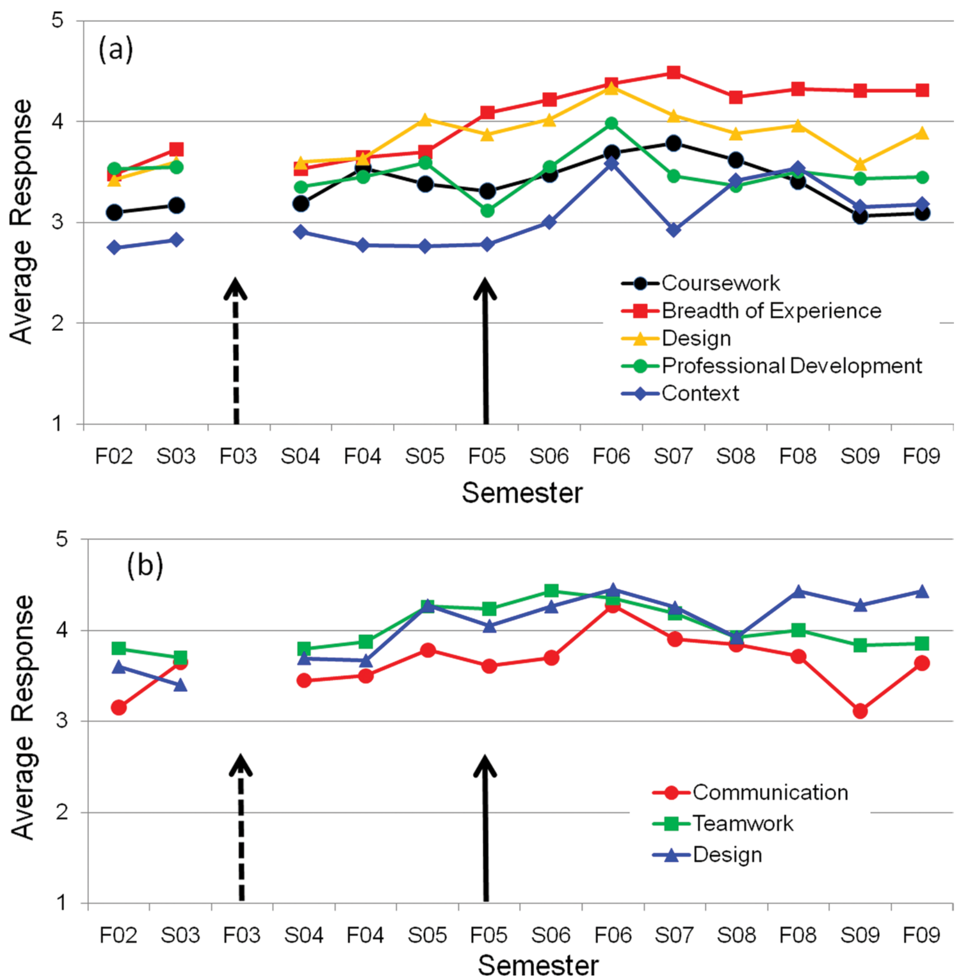

Figure 5. Changes in students' self-reported ability normalized to the control responses on coursework are shown in (a), while the design category is subdivided into design, communication, and teamwork in (b). The arrows represent the start of the planning (dashed) and implementation (solid) phases of the project.

abilities in teamwork since their basis for comparison may be peers who also have increased experience. Similarly students may judge teamwork skills on a small number of bad experiences that arise from their own lack of ability.

To measure conceptual understanding at graduation, a summative examination that draws questions from multiple, validated concept inventories is given at the end of the first, required capstone design course, taken in the senior year. Recently concept inventories have been developed for various topics in electrical engineering. ES21C combined eight inventories into a single examination to test students' understanding of fundamental concepts underlying electrical engineering in each of the different curricular areas of specialization taught by in the degree program. Approximately eight questions from each of seven separate inventories have been chosen as representing electrical engineering fundamentals. Faculty across the program ranked questions on a 1-5 scale on two criteria: 1) questions *every* student should be able to answer correct if they have understood basic concepts, and 2) questions that cover concepts that all students are taught at least once. The questions that were deemed easiest and most heavily covered were chosen for the exam. The test consisted of 52 questions given as a two-hour, closed-book final examination. All students finished within the two hour time limit. Sample sizes ranged from N = 51 to N = 12 students for the data presented. Of the eight areas covered by concept inventories, questions were separated by those that addressed topics covered in courses that had undergone reform under ES21C, and those that were not directly involved in reform. Since it wasn't possible to perform on a one-to one map between questions and specific courses, there is likely some overlap between the groups. Note also that unlike the usual format of concept inventories, the test was not given in a controlled pre-post format due to the wide range of questions.

Comparisons between aggregate scores (average of about 25 questions each) for ES21C-influenced and non-ES21C courses are shown in Figure 6 over a four year period beginning at the start of the project. Data is not available for earlier years. The data indicates that compared to non-ES21C courses, those courses which adopted the ES21C model show an increase in student's conceptual understanding over the four year period of the project. It should be noted that the composite concept inventory was given in the senior year and most courses which covered these topics are taken in the junior year. Thus it is not clear if the results are due to increases in conceptual understanding or a better retention of concepts. As with previous results, the breadth of the reform effort makes it impossible to say that the observed trend was caused by ES21C, but improvement in conceptual understanding are correlated with the ES21C teaching method.

To determine if ES21C's increased influence on engineering procedural knowledge impacted more traditional measures of student ability, the results of the Fundamental of Engineering (FE) exam were tracked over the project. The FE exam asks 120 questions covering the basics of general

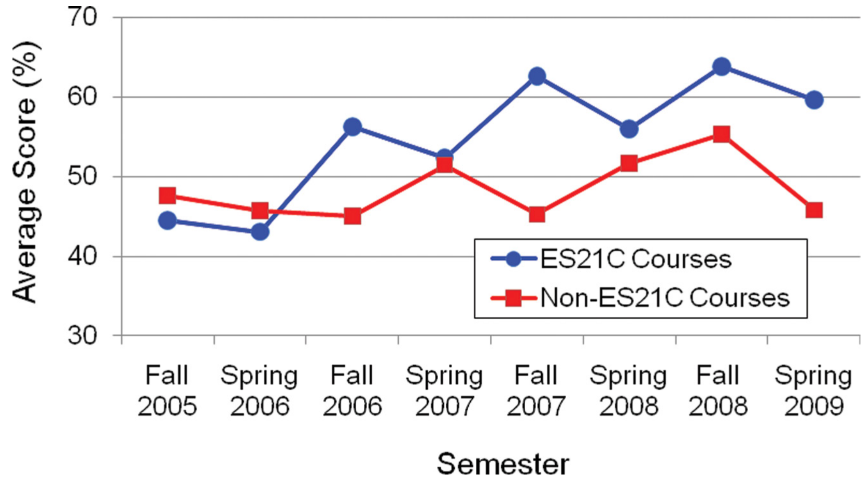

Figure 6. Average score over time on composite concept inventory given in the senior year for topics in ES21C and non-ES21C courses.

engineering and subject specific topics in two four-hour sessions. Students self-select whether to take the FE exam, with the program helping offset the cost of the examination. Generally between four and ten students take the exam each semester. To ensure that these students form a representative sample, the GPA of all students who take the exam is compared to all students in the program. The FE exam scores on all exam categories have been tracked over the duration of the project using the scaled-score method (LeFevre, et al., 2005). Scaled scores of ±1 correspond to variations of one standard deviation from the national mean. Despite the increased focus on design and projects there is no discernable loss on more traditional learning since scores on the FE exam have stayed relatively constant within errors of the measurement. Looking within categories of the subject exam, three categories can be mapped to ES21C courses, while six categories reflect content that is not directly taught in ES21C courses. Two of the three categories averaged for the ES21C data points were reformed in the initial phase of the project in 2003. Comparing ES21C to non-ES21C courses, there was a slight downward trend in ES21C courses, compared to other courses on the subject exam. A linear fit shows a 20% decrease over five years, as opposed to a 5% decrease for non-ES21C courses, but the drop is not statistically significant and the overall scores for both groups are comparable within the error. There is additionally more variation in year-to-year scores for ES21C courses, but it is not clear whether this is due to changes in learning outcomes or simply since this is a composite of three rather than six categories. It should be noted that due to the variable, and relatively small number of students taking the exam every semester that FE exam scores tend to fluctuate semester-by-semester.

To measure changes in student metacognition, the Metacognitive Awareness Index (MAI) was given in the sophomore and senior years (Schraw and Dennison 1994). The MAI has 52 questions that measure metacognition on two scales—knowledge of cognition (25 questions) and regulation of cognition (27 questions)—which are intercorrelated at $r = 0.45$. Responses are on a five point Likert scale with 1 corresponding to not at all true of the respondent and five very try of the respondent. Both sophomores and seniors mean scores were 3.8 on the knowledge of cognition and 3.3 on the regulation of cognition. There were no changes in MAI scores from the sophomore to senior years or longitudinal changes over time on either scale of the MAI.

In summary, data that measures overall outcomes, rather than specific course or learning objectives, paints a picture, while still incomplete, of students who encounter design problems more often and have multiple experiences with teamwork and communication in design, and value these experiences following graduation. This additional experience has been purchased at the expense of broad, preparatory courses, however long-term measures do not indicate any significant decrease in students' ability to solve traditional problems as measured by FE exam scores. Preliminary data shows that ES21C is also having a positive impact on students' conceptual understanding. It should be noted that the observed trends do not necessarily prove causation. A degree program is constantly changing and evolving, and other changes in how students learn cannot be ruled out as causing the observed changes to student learning.

DETOURS ALONG THE ROAD TO REFORM

In an ideal world a program for course reform that was based on research in how students learn and liberally lubricated with NSF funding would be embraced by faculty, implemented in courses, and student learning would improve. In reality there were unforeseen roadblocks on the path to reform. This section briefly discusses some of these obstacles and the changes to the project direction needed to overcome or bypass them.

Many of the unanticipated obstacles to reform that impeded ES21C in the first two years came from groups or individuals and could have been avoided with some forewarning. A lack of interest in program reform by some faculty was anticipated; the course-focused rather than curriculum-focused structure of ES21C was designed to bypass faculty who chose not to participate. The project did not, however, anticipate the active opposition to reform by a small number of individuals. The reasons for opposition to reform were difficult to clarify, but primarily arose from personal beliefs about teaching based on individual experiences, either good or bad. Other opposition arose from the perception that the six step model was prescriptive and that faculty were being forced to change their teaching, often in ways that ran counter to deeply held beliefs. The project also underestimated communication barriers between faculty who were conversant with engineering education research and those who were not. Some ES21C participants in OSU's College of Education are actively investigating the role of faculty beliefs in helping or hindering reform (James, et al. 2007).

The prescriptive view of reform likely arose from the conception, often implicit in engineering education literature, that there are "better" or "worse" ways of teaching. Many faculty who were engaged in ES21C were looking for a better way of teaching while those who opposed reform thought their teaching was being characterized as "worse". One of the changes in direction made during the project was to relax initial requirements of adherence to the strategic model outlined previously section. It was found that identifying learning goals for classes first, then suggesting changes to course structure or pedagogy from the elements of the ES21C strategy that supported faculty-identified goals was a more effective approach than starting with changes to pedagogy.

At the start of ES21C large meetings of all participants were held and education experts were invited to discuss effective teaching techniques. These meetings were generally unsuccessful; most faculty did not learn well from lecture. As the project evolved, the strategy shifted to holding one-on-one or small group meetings between faculty and a PI immersed in engineering education and the philosophy of ES21C. This approach, while demanding of PI's time, was more effective at creating effective and sustainable change.

The project also failed to anticipate the difficulties that arose from fundamental differences in structure between the traditional, knowledge-based and reformed, developmental courses. Traditional courses are highly linear since information and concepts build sequentially. Textbooks serve as signposts for different pathways to knowledge acquisition. In the ES21C model, course activities follow more of a design paradigm without a clearly defined, linear path. In ES21C what is learned depends upon the project used to scaffold learning, content is classified by a cognitive process level, and sequencing content is dependent on the chosen pathway to problem solution. Since this is the approach to learning that is often followed in research, it was anticipated that it would be familiar to faculty. Participants had difficulty, however, transferring their own metacognitive processes to create learning opportunities for students.

CONCLUSIONS AND SUSTAINABILITY

With, at the time the article was submitted, just over one project year remaining, *Engineering Students for the 21st Century* continues to change the culture of OSU's ECE department. While the pace of change has been slower than expected, the broad vision set forth by the project is slowly being implemented. As intimated by the Machiavelli quote at the start of this article, such change has not been easy and it is an open question whether the pace of change, or even the cultural change itself will be sustainable in the years following conclusion of the project. This section first comments on sustainability then concludes with several observations that may be valuable to other programs that seek to initiate wide-spread and aggressive reform efforts.

Engineering Students for the 21st Century, as initially conceived, focused on changing ten courses to engender program reform. In retrospect, the decision to implement change in individual courses likely arose from the predominance of course-level studies in the STEM education literature that provided clear guidance for reform at this level. While ES21C's emphasis on courses is robust, it will face pressures caused by faculty turnover, changes in course assignments, and shifts in faculty interest over time. To be sustainable, ES21C is first changing courses then integrating these changes into the degree program. Integration into the degree program has also been pursued by developing department-wide infrastructure and resources to support design as outlined earlier. Changes to department infrastructure support sustainable reform since such infrastructure is often maintained by staff with clearly defined responsibilities. ES21C is also examining ways to implement faculty reward structures, but since this requires cultural change at an administrative level, progress has been slow.

Another way that ES21C is trying to make reform sustainable is through synergistic efforts with external program evaluation such as ABET Some faculty think of ABET, if they think of ABET at all, as eleven vaguely worded outcomes, the (a)-(k) (ABET 2008). The inherent vagueness of (a)-(k), however, allows programs to interpret and personalize outcomes, as well weigh outcomes to support program reform. ES21C has aligned reform goals with ABET accreditation goals, engaged key faculty in the accreditation process, and developed common sets of evaluation metrics. Another pathway to sustainability integral to ES21C are the significant efforts to engage graduate students and young faculty in reform. Many of these efforts have occurred through partnerships with other organizations within the university rather than starting new efforts within ECE.

In retrospect, what advice can *Engineering Students for the 21st Century* offer to other programs interested in reform of engineering education, particularly programs without the generous funding provided by the National Science Foundation? First, recognize that the time constant of reform efforts is much longer than many other engineering projects. Most faculty participating in ES21C are also engaged in technical research projects that last from several months to three years. Program reform, which involves cultural change, has a time constant closer to a decade. Like physical systems, trying to drive a degree program at a rate much faster than the natural response time is extremely difficult and inefficient. A key first step is to try reform on a small scale and be willing to accept poor outcomes while experimenting. Several years of missteps are followed by successes by the pioneers; recognizable by the arrows in their backs. Initial successes are eventually discussed, mimicked with varying degrees of success, then adapted to meet faculty's beliefs and needs. To misquote Paul Samuelson, over time and funeral by funeral reform advances. It is critical, in our experience, that reform efforts have a clear, simple, and easy to communicate vision to serve as a guide star in order to maintain direction over the long term. ES21C did not initially realize this fact, and consequently has struggled to communicate the project vision to faculty.

One important observation is that the effectiveness of ES21C increased dramatically when infrequent large, formal meetings were replaced with more informal one-on-one or small group meetings held on a regular basis. While this placed significant time burdens on some faculty, it resulted in more lasting and significant change. Thus a second recommendation for others seeking departmental reform is to hire or support faculty who have backgrounds both in engineering education and technical fields. These faculty, who have credentials in technical research, serve as ambassadors to other faculty. It is important to note that such positions have been found to incur significant personal risk (Bush et al. 2008).

At the start of *Engineering Students for the 21st Century* the participating faculty were aware that students needed more individual choice in some aspects of their education in order to develop into engineers. In retrospect it is clear that ES21C failed to identify the same need in faculty. Some of the rocky start of the project could have been avoided had the primacy of faculty beliefs over engineering education research results been recognized. The importance of faculty beliefs is likely the root cause that working individually with faculty proved so effective.

How can programs interested in reform and faculty who have nagging doubts about how effectively we are educating the next generation of engineers adopt the ES21C model to their institutions without the generous support provided by NSF? While it is tempting to end this retrospective by outlining a "magic bullet" formula or procedure for reform, there are no magic bullets. The prescriptive approach was unsuccessful in the planning phase of ES21C, replaced with a more strategic approach in the implementation phase, then the strategy itself relaxed as the project evolved. It is more correct to think of program reform as a journey that is aided by guideposts, but is ultimately up to the traveler to undertake. If the program were, however, to redo the reform project with fewer resources, there are several lessons that would help prepare for the journey:

- Revamp existing labs and design courses by making changes to the learning environment that give students more freedom and flexibility. An investment of several hundred dollars of e-commerce software enabled ES21C to develop on-line catalogs that have made it easier for students to self-schedule time to work on problems.
- Create classes in which knowledge acquisition occurs outside the classroom and application of what is learned is done in class under guidance of the instructor. Lectures can be moved to video formats- a tablet computer, video capture software, and YouTube allow any faculty

member to self-publish on-line content for under $2000. Once on YouTube students have access to material at need, as do others across the globe.

- Give students opportunities to talk through complex engineering problems on their own terms without being told what they need to learn. Case studies, when properly implemented, are a cost- and time-effective way to give students a voice.
- Consider how the degree program could be structured so that course content is not the primary organizing principle. Content is important, it defines the degree, but content needs to be combined with application. The skills, attitudes, and experience students need to develop need to be identified separately from content. The engineering taxonomy (hyperlink) introduced earlier is one tool that can be used in reflecting on programs.
- In moving from a content-driven to development-driven program, ES21C has found it especially valuable to contextualize work around the design cycle shown in Figure 3, particularly for courses early in the program. All student work is related to the design cycle to help students understand how what they are doing fits into a larger picture.
- Know thyself. This aphorism should be interpreted two ways. First, clearly define the overall goals and direction for your program and how students should change as they advance towards a degree. While many programs dread six-year accreditation, ABET can be a powerful force for change when it is used as a goals-driven process rather than an externally imposed mandate. Second, recognize that faculty members' beliefs about teaching and learning likely arose from their personal experiences and preconceptions and do not universally apply to all students. Be willing to attempt teaching experiments even if they go against some beliefs in order to expand the repertoire of pedagogies available in the program.
- Develop in-house expertise in engineering education. While most faculty teach, few have much depth in the science of learning. Having a faculty member in the department who develops expertise in engineering education not only brings new perspectives, but can help externally fund reform efforts by submitting competitive proposals.

To conclude on a resounding note, it is tempting to end this paper with the claim that our program is better as a result of reform. As discussed previously, however, the concepts of "better" and "worse" lead to dangerous territory. Rather it can be concluded that our program is different, and the differences support the new conception of engineering education put forth by a multitude of national panels (National Research Council 2004, 2005, 2007, 2009 Hyperlink to these resources). Creating these differences has come at a significant cost of both resources and time. The authors, as do other participants, suffer moments of self-doubt in which we wonder whether the NSF resources put at our disposal have been used effectively and if the effort at reform has been worthwhile. The reflection and analysis required to write this paper have, however, reaffirmed the belief that department reform is not only worthwhile, but vital to our well-being as a discipline and as individuals. Reform requires us to listen to what author Parker Palmer calls our "inner voice". The journey is difficult; as Machiavelli intimated, there is much resistance to change, compounded by the difficulty of "proving" the value of reform. While there will always be doubt whether the journey of reform is worthwhile, as with Tinkerbell in the stage version of *Peter Pan*, doubt can itself be fatal. By looking deep within ourselves, by reflecting on our own values and those of our community, we can create ways for our students to discover for themselves the value of engineering, ways of developing those who will carry out the great works of this age. Context and culture are important; without stories, without tales of heroes, without a guiding mythology it is hard for many students to discover passion in a dispassionate discipline. At the end of the degree program is it more important for our students to share our knowledge or our culture?

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